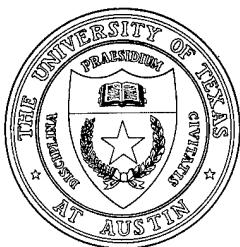


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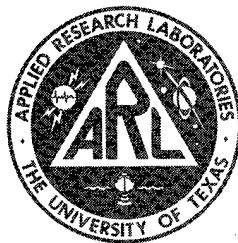
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**Nonlinear Acoustics:  
Self-Refraction in the Field of a Paraboloidal Reflector and  
Two-Ellipsoid System to Enhance Cavitation Collapse  
Seventh Annual Summary Report under Grant N00014-89-J-1109**

David T. Blackstock



**Applied Research Laboratories  
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P. O. Box 8029      Austin, TX 78713-8029**



15 August 1995

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1 October 1994 - 30 September 1995

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## **1. INTRODUCTION**

This is the seventh annual report under Grant N00014-89-J-1109, which began 1 October 1988. The research carried out under this grant is primarily in nonlinear acoustics. The broad purpose of the research is to determine the laws of behavior of finite-amplitude sound waves, especially to find generalizations of the known laws of linear acoustics. This report is for the period 1 October 1994 — 30 September 1995. See the sixth annual report (95-2)\* for status of the research at the beginning of the current report period.

The following persons participated in the research during the report period:

### **Graduate students**

- Michael R. Bailey, Ph.D. student in Mechanical Engineering
- Lawrence J. Gelin, M.S. student in Mechanical Engineering; degree awarded May 1995

### **Senior personnel**

- D. T. Blackstock, principal investigator

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\*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 95-2 means the second entry in the list for 1995.

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## 2. PROJECTS

The following projects were active during the report period:

- 2.1 Self-Refraction in the Field of a Paraboloidal Reflector. This project has been completed. The variation in particle velocity along each wavefront of an inhomogeneous plane wave causes the wavefront to bend. The effect, called self-refraction, has been demonstrated in an experiment in which a paraboloidal reflector, with a spark source at its focus, produces the inhomogeneous plane wave. Calculations based on the KZK equation and other known models were made to provide a comparison between measurements and theory.
- 2.2 Two-Ellipsoid System To Enhance Cavitation Collapse. Two half-ellipsoid reflectors, one pressure release, the other rigid, are positioned in water so that they have a common far focus. Each has an electric spark at its near focus. The pressure release ellipsoid is fired first. The primarily negative pulse at the far focus generates a cavitation bubble there, which grows and then collapses. The rigid ellipsoid is fired so that its strong positive pulse arrives just in time to accelerate the bubble collapse. The violence of the collapse and the concomitant destructive action should therefore be enhanced. The project is primarily experimental and has application to lithotripsy. It may also be useful in showing a way to control cavitation.
- 2.3 Miscellaneous. In this category are (1) preliminary experimental work on an acoustitron, which was shelved in favor of the ellipsoid project, (2) calculations about the edge wave from ragged edge apertures and disks, and (3) public disclosures about previous work.

### 2.1 Self-Refraction in the Field of a Paraboloidal Reflector

Gelin's M.S. thesis (95-1) completes this project. Self-refraction is bending of rays due solely to finite-amplitude effects, as opposed to ordinary refraction, which is caused by sound speed variation in an inhomogeneous fluid. An introductory discussion of the project is given in the previous annual report (95-2). The following abstract of Gelin's thesis, submitted for publication in the Technical Notes and Research Briefs section of *J. Acoust. Soc. Am.*, summarizes the investigation:

"A primarily experimental study of the sound field produced by a paraboloidal reflector with an electrical spark at its focus is presented. The spark creates a spherically spreading N wave, which on reflection from the paraboloid becomes an inhomogeneous plane wave beam. The wavefront is plane but the amplitude decreases with transverse distance  $R$  from the beam axis. The combination of amplitude shading and nonlinear propagation distortion causes the wavefronts to become curved, convex for the positive part of the N wave, concave for the negative part. This effect is called self-refraction. Experiments were done in air with two different reflectors (one machined aluminum, one made by spinning a bowl of epoxy), focal length  $\approx 5.1$  cm, aperture radius  $\approx 10.5$  cm. The N wave peak pressure  $\hat{p}$  and half duration  $T$  were measured across the beam at various axial distances  $z^*$  from the aperture.\* The range of measurements was  $R \leq 8$  cm and  $15 \text{ cm} \leq z^* \leq 90$  cm. Self-refraction was pronounced for strong N waves ( $\hat{p} \approx 1100$  Pa,  $T \approx 6 \mu\text{s}$ ), less noticeable for weak N waves ( $\hat{p} \approx 400$  Pa,  $T \approx 3 \mu\text{s}$ ). Edge waves were also measured. Supporting theoretical work was based on geometrical acoustics, weak shock theory, and the KZK equation. [Work supported by ONR.]"

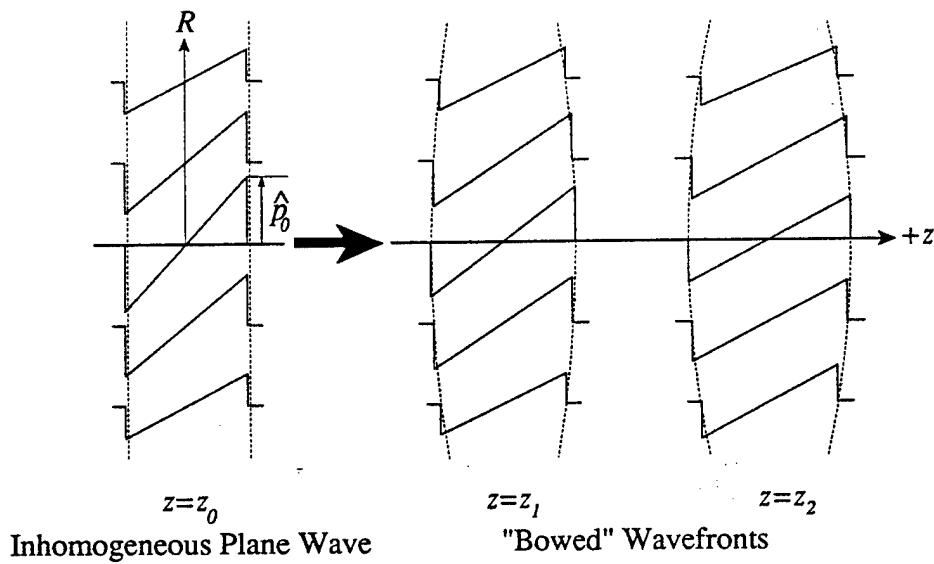
Figure 2.1 conceptualizes self-refraction. The N wave beam is similar to that produced in Gelin's experiment. Because the N wave is strongest in the center of the beam, the head shock travels fastest on the axis, slowest on the edge of the beam. As the wave propagates, therefore, the head shock wavefront becomes convex. The subsonic tail shock, on the other hand, travels slowest in the center of the beam, and thus its wavefront becomes concave. One therefore anticipates that the spreading of the head shock (and all positive parts of the wave) will cause it to decay, while the convergence of the tail shock (and all negative parts) will cause it to grow. Since these are expected to be higher order effects, however, we made no attempt to observe them.

One way to quantify self-refraction is to measure its effect on the half duration  $T$ . Figure 2.2 shows waveforms calculated by a computer code called KZKpulse, which is based on the KZK model of the beam.<sup>1</sup> Measured data at the measurement plane closest to the aperture,  $z^* = 15$  cm (see Fig. 2.4), is used as the input to KZKpulse. The wave is assumed still plane at this distance, but shaded in amplitude as shown by Fig. 2.4. Figure 2.2 shows that the on-axis segment of the head shock arrives several  $\mu\text{s}$  ahead of the edge-of-the-beam segment, while the reverse is true for the tail shock.

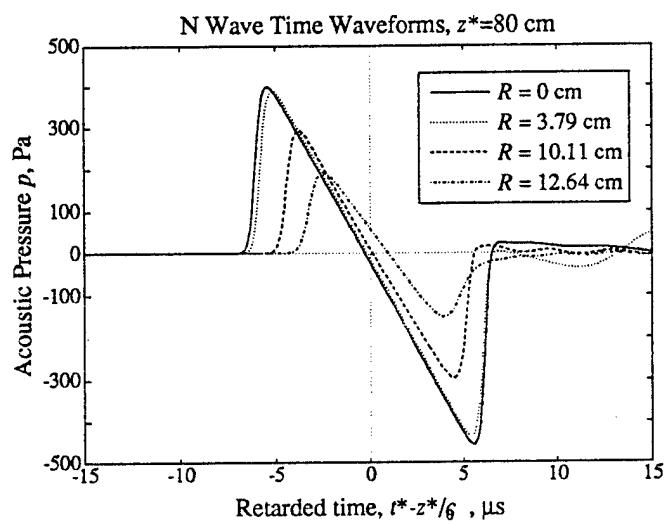
A sample of the experimental results is shown in Fig. 2.3. Measured values of  $T$  are shown across the beam for various distances  $z^*$ . The increase of  $T$  with  $z^*$  is greater in the center of the beam than at the edge. This is an experimental demonstration of self-refraction. Although the magnitude of the effect is not as great as that shown in Fig. 2.2, self-refraction is clearly present.

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\*Because of the slight asymmetry of spark-generated N waves,  $T$  here always refers to the positive half of the wave.

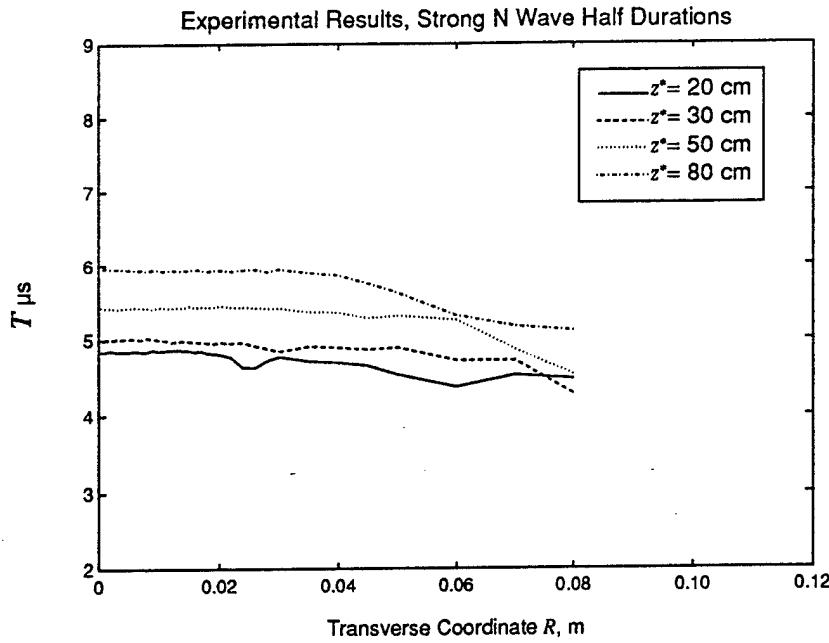


**Figure 2.1**  
Propagation of an inhomogeneous plane N wave of finite amplitude  
(spatial waveforms)



**Figure 2.2**  
Calculation (KZKpulse) showing the effect of self-refraction on N wave duration. Distance from the aperture  $z^*$  is constant, transverse distance  $R$  varies.

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**Figure 2.3**  
**Measured half duration  $T$  as a function of  $R$  at various axial distances**  
 AS-95-998

The mysterious drop in amplitude of the N wave near the axis, illustrated by the data shown in Fig. 2.4, was the object of considerable attention. Although several possible causes for the dip were considered (see the previous annual report, 95-2, Sec. 2.2), the most likely candidate is believed to be localized heating of the air by the spark. The axial part of the reflected wave must pass through the "hot spot." The heated air acts as a tiny diverging lens, which refracts paraxial rays away from the axis. Gelin attempted to account for the effect of the hot spot on the wave field. He used a heat conduction code, along with information about the heat energy released by the spark, to estimate the temperature distribution at the time the reflected wave reaches the spark position (about  $294 \mu s$  after the firing of the spark). At this time the radius of the hot spot is estimated to be about 1 mm, over which the sound speed drops from about 550 m/s at the center to the nominal value (343 m/s) at the edge. The next problem was how to make use of this information in computing the pressure field outside the reflector. Since it was not possible to begin the KZKpulse calculation in the plane of the spark (the pressure could not be measured there), he modified the data input to KZKpulse (at the starting plane  $z^* = 15 \text{ cm}$ ) by including the effect of the hot spot on paraxial ray arrival times. The result of the calculation was disappointing: the new arrival times had little effect on the pressure field predicted at subsequent distances  $z^*$ . We conclude that if spark heating is the cause of the axial dip, a better way of (1) estimating the temperature distribution in the spark region, and/or (2) incorporating its effect on the propagation, will have to be found.

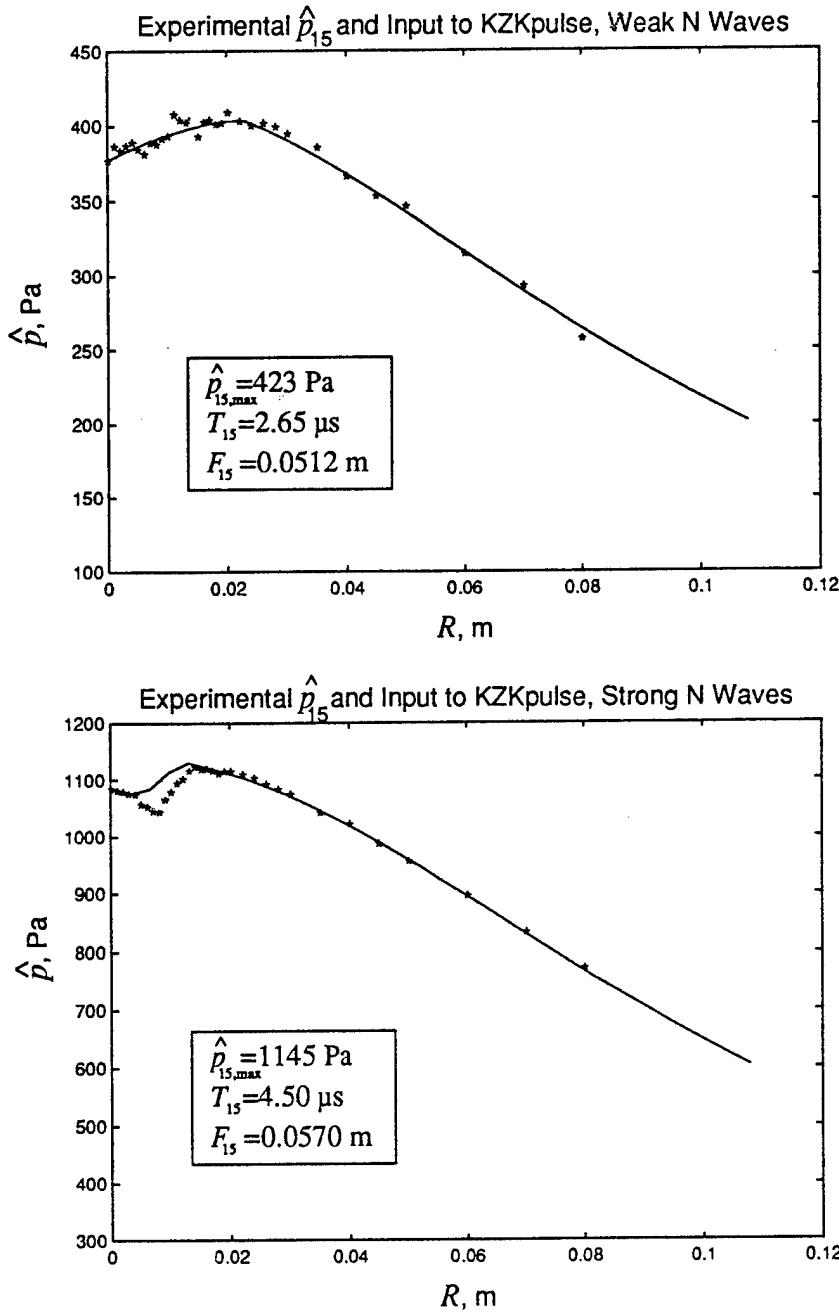


Figure 2.4  
Data for  $\hat{p}_{15}$  (peak pressure at  $z^* = 15 \text{ cm}$ ). Solid curve is a fit to the data that serves as the input to code KZKpulse.

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## 2.2 Two-Ellipsoid System To Enhance Cavitation Collapse

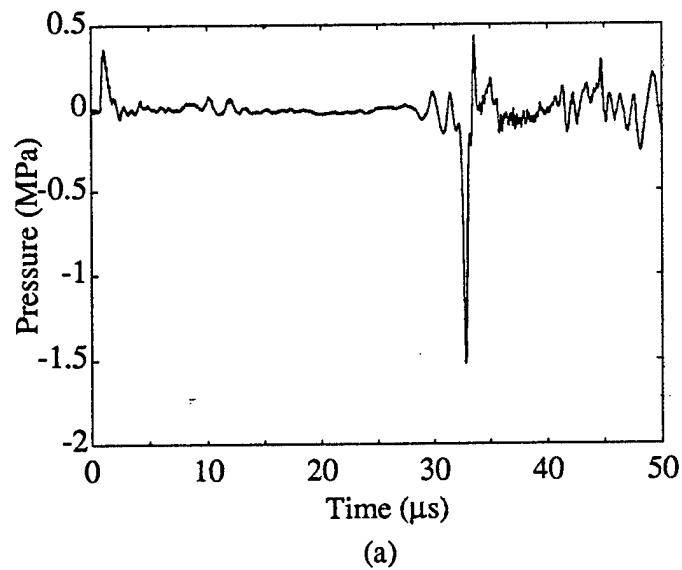
This project is Bailey's doctoral topic.\* The idea that led to the project came from L. A. Crum during a visit to our laboratory in 1992. On seeing Bailey's apparatus for generating an isolated negative pulse (92-3, 93-3, 94-1), Crum asked Bailey whether he could follow the negative pulse with a positive one. The role of the negative pulse would be to generate a cavitation bubble, that of the positive pulse would be to accelerate the bubble collapse and thereby to increase the bubble's destructive action. Since that time Bailey considered various ways to generate the two-pulse sequence. He finally decided on using two ellipsoidal reflectors each having a spark at its near focus, after the design of the Dornier lithotripter. To produce the negative pulse, however, a pressure release reflector would have to be used. Up to now the only work reported on pressure release ellipsoids is that by Müller.<sup>2</sup>

Bailey has machined pressure release ellipsoidal reflectors out of polyurethane foam and rigid ellipsoidal reflectors out of aluminum. Each reflector is half an ellipsoid and has the same dimensions as the reflector used in the Dornier HM3 lithotripter: semi-major axis  $a = 13.8$  cm, semi-minor axis  $b = 7.75$  cm, focus  $c = 11.42$  cm ( $2c$  is the distance between foci and  $c = \sqrt{a^2 - b^2}$ ). The reason for duplicating the Dornier design is that many laboratories have done measurements with and calculations for the Dornier ellipsoid. Indeed, we are collaborating on this project with E. L. Carstensen's group at the University of Rochester, and it is very useful to use the same size reflectors so as to be able to compare measurements. We have recently received from Rochester a brass ellipsoidal reflector (the impedance of brass is more than twice that of aluminum) used in the Coleman lithotripter,<sup>3</sup> which also mimics the Dornier design. Two types of electrodes have been used: the end of a coax cable and the Dornier electrode. In Bailey's current design a Dornier electrode fits snugly through a hole in the wall of the ellipsoid and is held rigidly in place by a fixture on the outside. A capacitor of  $0.06 \mu\text{F}$  charged to 20 kV delivers a spark energy of 12 joules; sparks of smaller energy have also been used. An NTR piezoceramic probe hydrophone, which has a 10 MHz passband (but not flat), is used to measure the field.

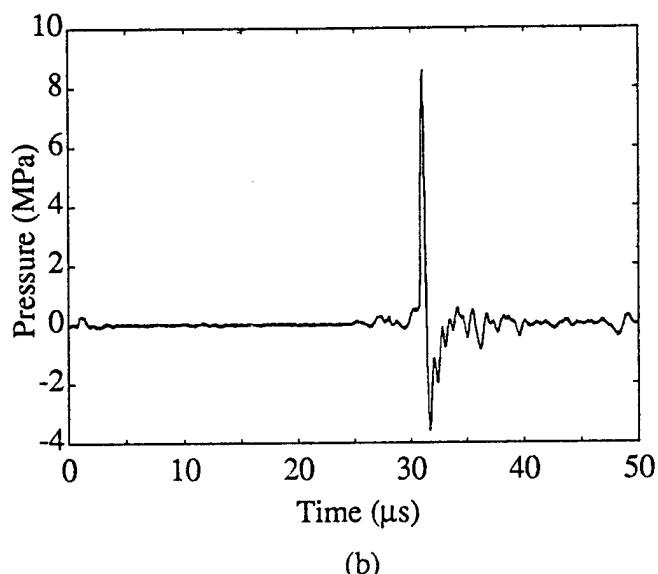
Figure 2.5 shows samples of the pressure waveforms that have been measured. The hydrophone is at the far focus. The top trace, Fig. 2.5(a), is for a pressure release reflector. The small positive pulse near the beginning of the trace is the direct wave; the large negative pulse about  $32 \mu\text{s}$  later is the reflected, focused pulse. It can be seen that the gain is about 5, close enough to the gain of 7 that Müller achieved to be encouraging. Ironically, after the measurement was made, Bailey discovered that he had located the spark gap a little off focus. When he made a new reflector

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\*Bailey earlier considered another topic, the acoustitron, work on which is reported in the previous annual report (95-2). During the present report period, however, largely because of Bailey's enthusiasm, a decision was made for him to switch to the two-ellipsoid project.



(a)



(b)

**Figure 2.5**  
Waveforms of the focused pressure pulse from an ellipsoidal reflector.  
(a) Pressure release reflector   (b) Rigid reflector

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with the spark gap positioned exactly at the focus, the waveform he measured was worse, not better, than the one shown in Fig. 2.5(a). A new design to allow some adjustment in the electrode position is being considered.

Figure 2.5(b) shows the waveform for the brass reflector. Because of the scale used, the direct wave is only just noticeable. The gain is seen to be about 25 (the gain for an aluminum reflector is about 10). Although the amplitude of the focused pulse, about 9 MPa, is far below that achieved by the Coleman and Dornier lithotripters,<sup>3</sup> much remains to be done to optimize the circuitry. LithoTech (Atlanta, Georgia) has recently donated to us the shock wave generating parts of a Dornier and a Medstone lithotripter (both clinical machines). Having these systems available should help us increase the amplitude of our pressure signals.

The timing circuit needed to provide a precise interval between the firings of the two ellipsoids has been built. Tests at lower voltage (8 kV) show that the circuit works well.

After the ellipsoid hardware and the electrical and timing circuits have been optimized, the next problem will be to detect bubbles and monitor their activity.

### 2.3 Miscellaneous

Theoretical work on the acoustitron during the previous report period (95-2) was followed by construction of a small acoustitron intended to be energized by two horn drivers. Although a few measurements were made, the project was not continued. It was decided that Bailey should give his full attention to the ellipsoid project.

In earlier work on diffraction by ragged-edge apertures and disks (92-3, 93-3, 94-2, 94-6, 94-9, 95-4) the edge wave was disposed of simply by a purely qualitative argument: since the signals arriving from various parts of the edge are incoherent, their sum is negligible. We have recently calculated the rms value of the edge wave for a variety of different signals (sine wave, noise, and pulses) and found the conditions under which the edge wave is indeed negligible (95-6).

Oral and written papers on earlier completed work include ones on negative pulse production (94-2, 94-6, 94-9, 95-4), scattering of sound by sound (94-10), and Bloch waves (95-5).

### 3. SUMMARY

During the current report period, 1 October 1994 – 30 September 1995, research was done on the following principal projects (student's name shown in parenthesis):

1. Self-refraction in the field of a paraboloidal reflector (Gelin)
2. Two-ellipsoid system to enhance cavitation collapse (Bailey)
3. Miscellaneous

Project 1, begun in 1993, was brought to a conclusion. Gelin's M.S. thesis (95-1) shows how self-refraction is realized in the reflected wave field from a paraboloidal dish that has an electrical spark at its focus. Besides the thesis, the project produced two oral papers (94-7, 94-8). A journal article is planned. Project 2 began this year. Both rigid and pressure release ellipsoidal reflectors have been constructed, fitted with electrodes, and tested. The timing circuit to regulate the sequential firing of the two ellipsoids has been built and successfully tested at low voltage. Miscellaneous topics include experimental work on an acoustitron and calculation of scattering from ragged-edge apertures and disks (95-6).

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and

Predecessor Contract N00014-84-K-0574 (ended 9-30-88)

	<u>Code</u>	<u>ONR Grant/Contract</u>
B	= chapter in a book	1109 = N00014-89-J-1109,
J	= journal publication	began 10-1-88
Js	= submitted for journal publication	0574 = N00014-84-K-0574,
O	= oral presentation	ended 12-31-88
P	= paper in a proceedings	
T	= thesis or dissertation	0867 = N00014-75-C-0867
TR	= technical report	ended 8-31-84

1988

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| 0574 | J | <sup>a</sup> 1. M. F. Hamilton and D. T. Blackstock, "On the coefficient of nonlinearity $\beta$ in nonlinear acoustics," <i>J. Acoust. Soc. Am.</i> <b>83</b> , 74-77 (1988).   |
| 0574 | O | <sup>b,c</sup> 2. D. T. Blackstock, "Shock wave propagation and shape of the waveform," Conference on Lithotripsy (Extra-Corporeal Shock Wave Applications - Technical and Clinical Problems), University of Florida, Gainesville, Florida, 12-13 March 1988.  |
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<sup>a</sup>Hamilton's support for this work came from Contract N00014-85-K-0708.

<sup>b</sup>Primary support for this work came from University of Rochester, NIH Grant CA 39241.

<sup>c</sup>Supported in part by a grant from Bureau of Engineering Research, College of Engineering, The University of Texas at Austin.

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- 0574      TR    5. D. T. Blackstock, "Nonlinear Acoustics: Reflection and Refraction, Scattering of Sound by Sound, and Periodic Media," Fourth Annual Summary Report under Contract N00014-84-K-0574, Technical Report ARL-TR-88-30, Applied Research Laboratories, The University of Texas at Austin, 30 June 1988 (AD A197614).
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<sup>§</sup>Supported in part by ONR, under several different grants and contracts, and by several other sponsors.

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<sup>d</sup>Primary support for this work came from Applied Research Laboratories IR&D Program and Texas Advanced Research Program.

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\*Supported in part by Applied Research Laboratories IR&D Program.

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<sup>f</sup>Maynard's support for this work came from an ONR contract at Pennsylvania State University.

<sup>g</sup>Supported in part by NIH Grant CA 49172 and by University of Rochester NIH Grant CA 39241.

1990 (cont.)

ONR

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<sup>h</sup>Primary support for this work came from NASA Grant NSG 3198.

<sup>i</sup>Hamilton's support for this work came from Grant N00014-89-J-1003.

<sup>j</sup>Supported in part by Grant N00014-J-90-1373.

1991

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<sup>k</sup>Supported in part by Grant NAG-1-1204 and University of Southampton, England.

1992

ONR

Contract    Code

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<sup>1</sup>Supported in part by ONR Grant N00014-89-J-1103, Applied Research Laboratories IR&D Program, and David and Lucille Packard Foundation.

<sup>m</sup>Supported in part by NIH grant at University of Rochester.

<sup>n</sup>Supported in part by NIH Grant CA 41972.

1993

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<sup>o</sup>Supported in part by NASA Grant NAG 1-1615.

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